MT. LOGAN

FIELD REPORT

G. HOLDSWORTH

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Department of the Environment
Glaciology Division

Unpublished Report

May, 1976

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1975

Introduction:

A topographic survey carried out in July, 1974 on the plateau of Mt. Logan, resulted in the establishment of control points within range of the NW Col. In July, 1975, this control was extended to span the NW Col and include Prospector's Peak. Figure 1 shows the structure of the survey done in 1975, and the location of sites referred to in the text.

Although Keeler (1969) and Labelle (unpublished) both made snow stratigraphic measurements in the region of the AINA camp and the NW Col (Fig. 1) it was considered necessary to get deeper information at the NW Col and to re-examine the $\delta^{18}O$ variation at that site (West, 1972) in more detail. The results obtained so far tend to justify this action. For instance, Keeler's firn temperatures at 10 to 15 m depth at the AINA camp are more than 4°C warmer than those at corresponding depths at the NW Col in 1975. Even though Keeler's measurements were taken 6 years earlier, some temperatures taken by Labelle in 1969 at the NW Col site about 2.6 m below the surface, agree fairly closely with ours. These measurements were taken at about the same time of the year as our own (July). Furthermore, whereas Keeler determined at the AINA camp site a 15 m depth-density curve which was practically identical with our own at the NW Col, the accumulation rate at the AINA camp site is more than 60% and possibly 100% greater than at the NW Col site less than a kilometer away. Considering the temperature shift between the two sites, Gow's (1968) "rule of thumb" for density curves is for practical purposes, verified. This interpretation however, leaves us with the problem of explaining the 4°C temperature difference between

that because of the lower density of the firn (compared with that of pure ice) it is likely to be more easily deformed for these stresses. Also, strong converging flow at the AINA campsite area would be responsible for an increase in longitudinal flow rate there.

Another independent estimate of horizontal strain rates* can be obtained from a knowledge of the accumulation rate at the NW Col and assuming a steady state surface with time. Under these conditions and assuming a constant accumulation rate of snow of 1.4 m a^{-1} and a 60 m thickness of firn of average density about 0.66 Mg m^{-3}, a vertical strain rate of about 10^{-2} a^{-1}, should result. Since the lateral (horizontal- NE/SW) component is likely to be small compared with the longitudinal component we therefore expect a down glacier component of the same order, although since the condition of incompressibility hardly applies here, it should be somewhat less than 10^{-2} a^{-1}.

Snow pit and core hole at the NW Col site:

A 2 m snow pit was dug on the crest of the col next to the striped pole marked: NW COL. At the base of this pit, which was then provided with a cover, a 13.8 m SIPRE core hole was drilled. All the core was saved. However, because of logistics problems, the entire core was not sampled. Nevertheless the remaining parts of the core are retrievable. Samples averaged 8 cm in length with about 5 cm spacings. At the AINA camp 137 such samples were melted down in sealed plastic bags and decanted into 20 ml plastic bottles. On their arrival in Ottawa, the volume of about 50 of these sample bottles was reduced to 10 ml by taking 10 ml from each for tritium

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* From the 1974 and 1975 surveys, the sinking rate of the top of the AINA mast is 1.8 m a^{-1}. This gives a mean column vertical strain rate of ~ 1.3 x 10^{-2} a^{-1}, since the thickness there is ~ 137 m.

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analysis. These samples were originally determined to be from firn spanning the key 1963 layer or to be close enough (on the upper side) that the position of the 1963 layer could be determined. The tritium analysis was done by Dr. H. Taniguchi of the Department of Health and Welfare, Ottawa. The remaining sample bottles were sent to the Geophysical Isotopes Laboratory in Copenhagen for $\delta^{18}O$ analysis. The results are shown in Figure 2, with a tentative age interpretation attached, and Figure 3.

Stratigraphy may be determined with difficulty by visual means, aided by hardness tests, and by density measurements, etc. for only 1 or possibly 2 years, because after about 3 m depth the stratigraphy seems to be obliterated. We determined a 1974/75 accumulation of 1.49 m of snow. Labelle (personal communication; unpublished) determined at approximately the same site an accumulation of 1.30 m of snow (average density 0.32 Mg m^{-3}) for 1967/68. Densities (Fig. 4) were determined in the upper 2 m using a standard density tube and spring balance; in the lower parts by carefully cutting the snow/firn core and calculating its volume from its dimensions and weight in air. This was necessary since we could not bring core samples down from the mountain. Densities are not corrected to in situ temperatures, a procedure which is thought unnecessary in view of the method used. In spite of this the depth-density profile appears to be quite reliable, as will be discussed.

Temperature measurements in the core hole were determined with a single thermistor (Y.S.I. #44033 ± 0.1°C type) and the temperature profile is shown in Figure 5.

It may be seen that the depth-density profile as determined in 1975 closely matches the one determined by Keeler in 1969 some 650 m away at the AINA campsite. Furthermore, Labelle's (unpublished) 1968 values for the

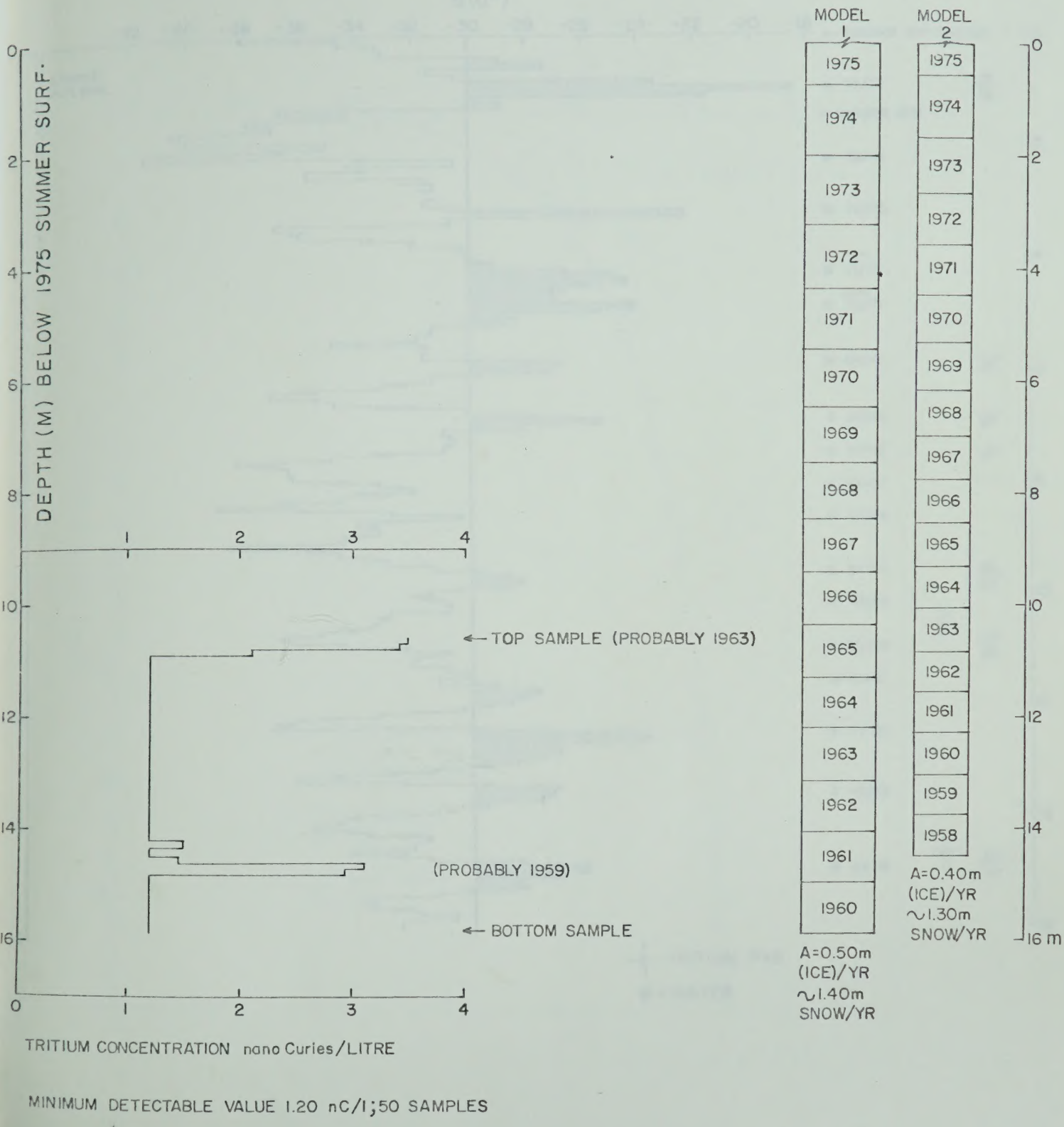
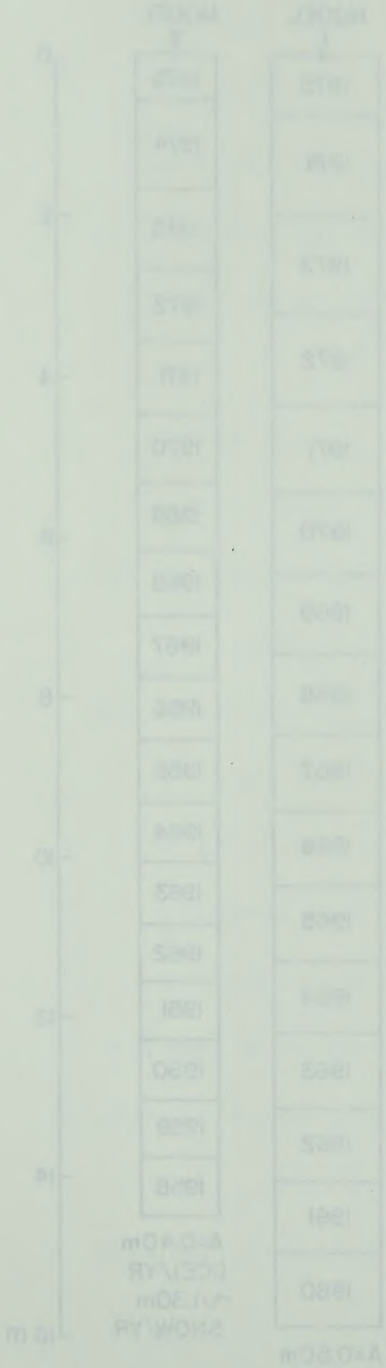


Fig. 2. Tritium variation with depth at NW Col site.



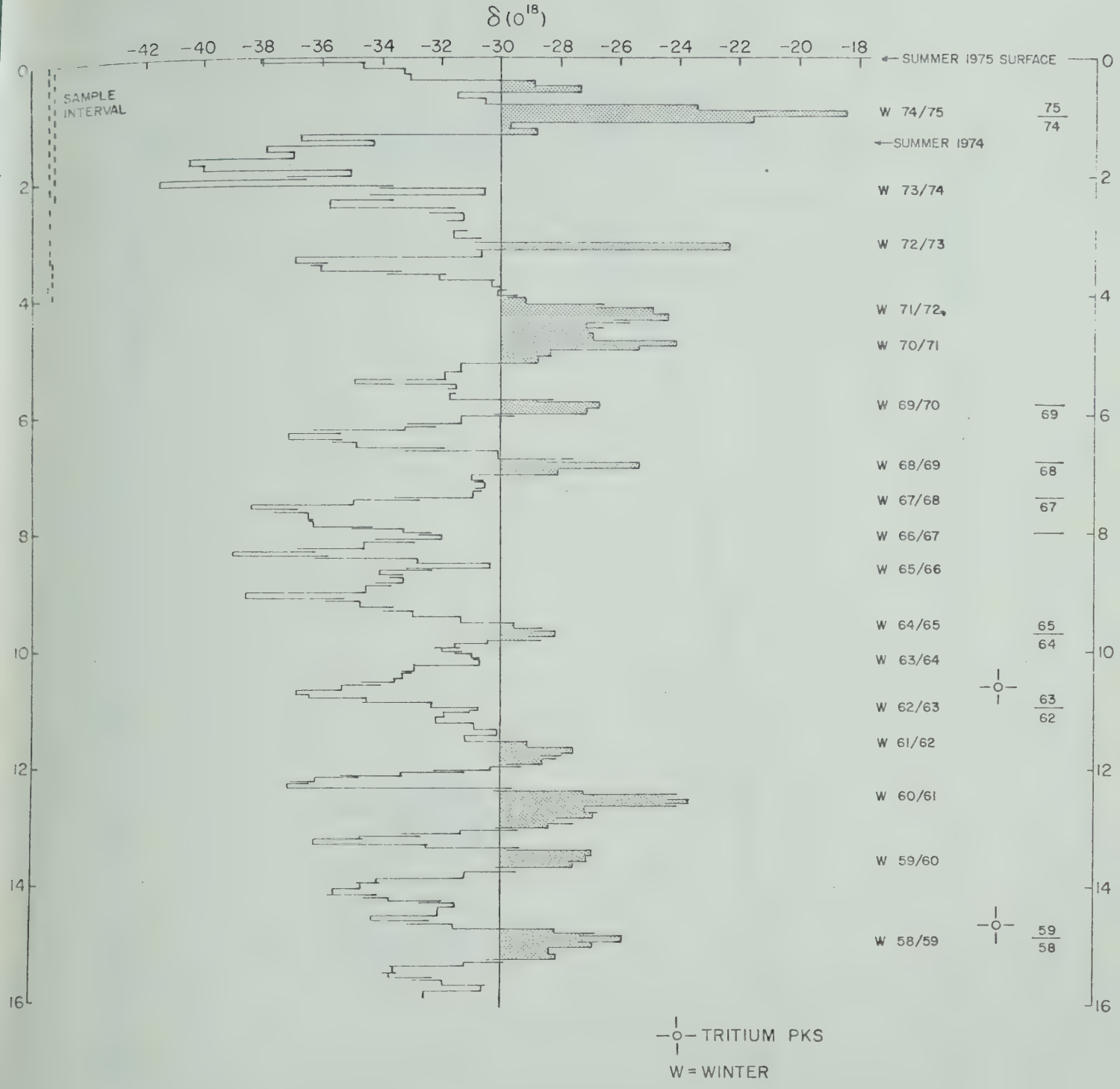


Fig. 3. $\delta^{18}O$ variation with depth at NW Col site.

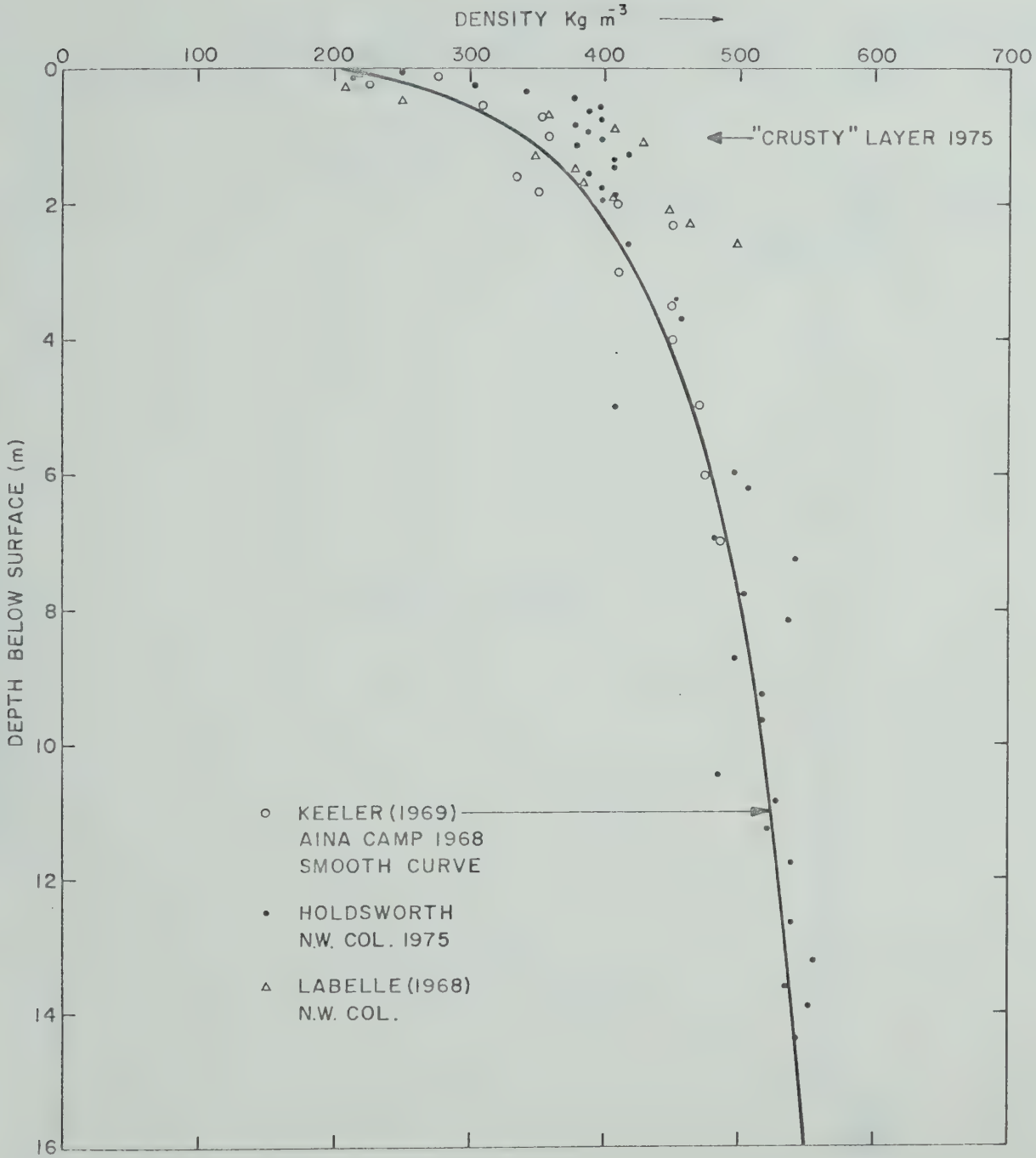


Fig. 4. Depth-density curve for the NW Col site.

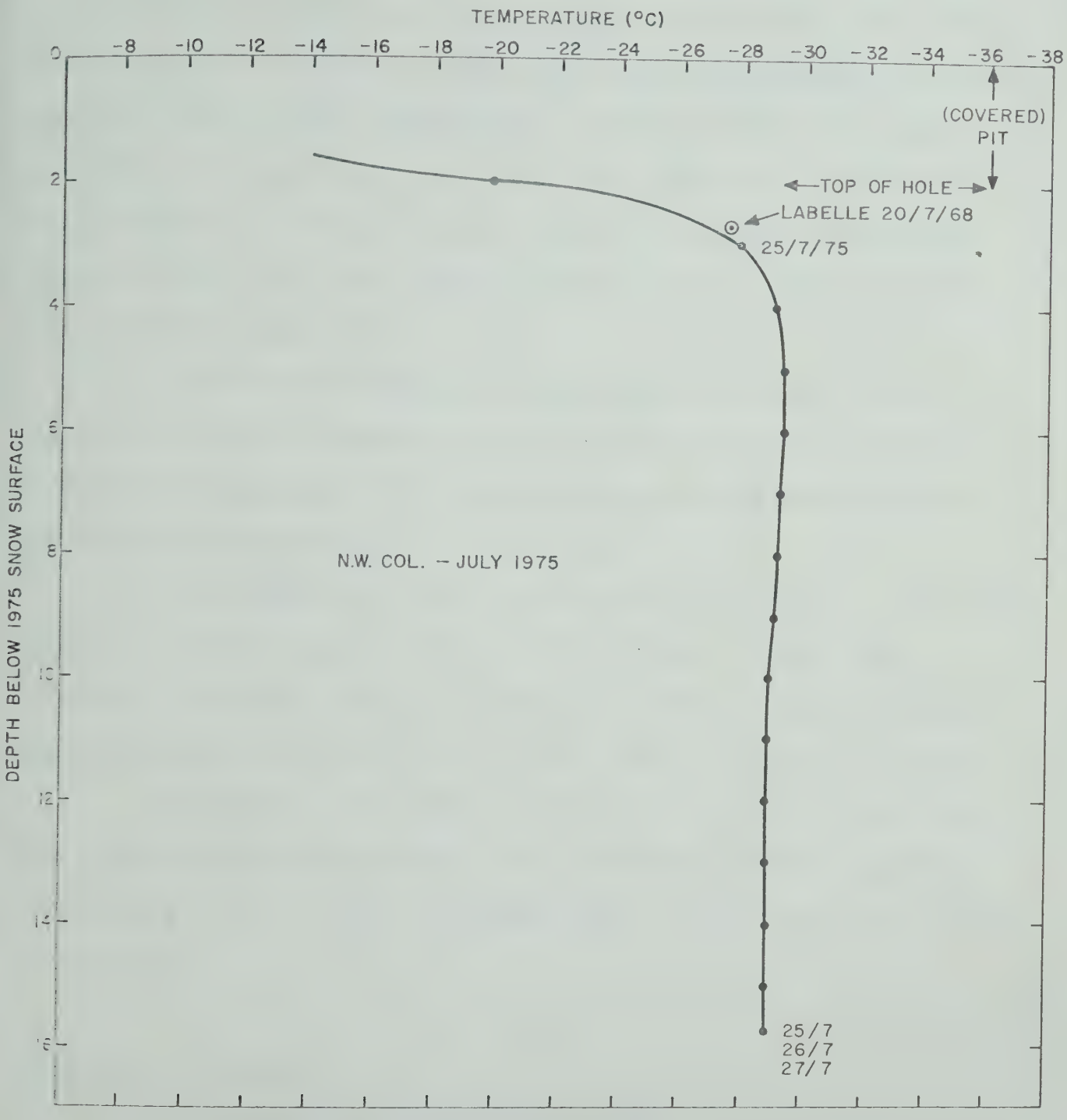


Fig. 5. Vertical temperature profile at the NW Col site.

upper 2.5 m at the col site also fall close to our own, which show a slight bulge towards higher densities at about 0.5 m depth. These values were associated with a slight "crust" (but not ice) at that depth. This "crust" seemed to be quite general, as it also occurred around the AINA camp and its existence is not strictly accounted for, although it is possibly caused by abnormally high temperatures and/or high winds. The error in our density values should be no more than about 0.01 Mg m^{-3}, and should not therefore change it significantly with respect to Keeler's curve. Furthermore these errors should be random ones.

The 10 to 15 m temperatures measured by Keeler were close to -24.5°C; we measured temperatures close to -28.9°C at the same depths, and, at least in the upper parts of the profile, Labelle's 1968 temperatures on the NW Col corroborate ours.

These differences (and similarities) may be explained by the known difference in the accumulation rates at the two sites. Keeler (1969) determined a value of 2.0-2.5 m a^{-1} for his site which is about 60% to 100% higher than our value of 1.49 m and Labelle's value of 1.30 m at the NW Col.

According to Gow's (1968) "Rule of thumb": "...to maintain the same depth-density profile, doubling the accumulation rate would require a temperature increase of 4°C." We therefore have a viable explanation for our observations.

Depth-Time relationship:

For convenience of computation, we seek an analytical expression:

$$\rho = \rho(h) \qquad (1)$$

where ρ is density, and h is depth below the surface. For our purposes it is sufficient to curve-fit within the interval 0 → 16 m, which is the limit of our present data, although it would not be difficult to extrapolate our data on the basis of Gow's and other's work in Greenland and the Antarctic. It is found that a polynomial of the form:

$$\rho = a + bh + ch^2 \tag{2}$$

is a suitable function to fit to the data for this interval, provided the lower end of the group of data is extended smoothly beyond the required limit of the maximum depth value by some means. Under no circumstances should this curve be used beyond the specified limits (16 m in this case). For large depths, where the basal or near basal material is approaching the density of solid ice, an equation of the form:

$$\rho = \frac{\rho_i \exp(sh)}{1 + w.\exp(sh)} \tag{3}$$

can be used with good results. In (3), ρ_i, s and w are constants. Using equation (2) an initial least squares fit yields:

$$a = 0.338, \quad b = 0.03306, \quad c = -0.00136.$$

Applying Sorge's Law (Bader, 1960):

$$\int_0^h \rho(h)dh = 0.338h + 0.01653h^2 - 0.000453h^3 = At \tag{4}$$

where A is a constant (average) accumulation rate and t is the age of the layer at depth h. As an immediate check on this formula we solve for t when h = 1.3 m and A = 0.41 m (water equivalent) (Labelle's values), and get t = 1.16 yr, whereas the correct solution is t = 1 yr. For h = 15 m, t = 18.1 yr. This is a probable upper limit as shown by the next calculation. An improved value may be obtained by making a synthetic correction to the lower part of the curve which gives rise to equation (4). In order to avoid a maxima from developing at the lower end (h = 16 m), we have injected the least squares program additional (synthetic) data there. Alternatively, to produce the same effect, we could have used depth-density data from other sources to extend the range and ensure that the curve fit is visually acceptable up to the point where our own data ends. For this reason the equation is only valid in the interval 0 to 16 m. Following this procedure, a better solution is now:

$$t = \frac{1}{A}\,(0.34023h + 0.01553h^2 - 0.000393h^3). \qquad (5)$$

If we take again Labelle's figures: h = 1.3 m; A = 0.41 m a^{-1}, t = 1.14 yrs at the base of the annual layer (instead of 1 year) and at h = 15 m, t = 17.7 yrs. If we take the mean of Labelle's and Holdsworth's data:

$h = 1.4$ m (for t = 1 yr)

$\bar{\rho} = 0.357$ (cf. Holdsworth's $\bar{\rho} = 0.349$ Mg m^{-3})

$A = 0.50$ m a^{-1}

then t = 1.01 yr at h = 1.4,

and t = 14.5 yrs at h = 15 m, or, the age of this depth layer is the

1960/61 boundary. Our initial estimate of the depth of the 1963 layer was based on the calculation using $A = 0.50$ m a^{-1}. The tritium analyses indicates that the 1959 peak is present and the start of the 1963 layer. This enables us to compute an average accumulation rate over the last 16 years (0.45 m a^{-1}). Such a figure can now be used in the Dansgaard-Johnsen model for determining the depth-time curve for the full ice column reaching to bedrock. This requires a knowledge of the depth at the NW Col site.

Depth determination

A basic version of R.H. Goodman's 620 mHz radio echo-sounder (Goodman, 1975) was operated at the AINA campsite on July 22, 1975. Because of logistics constraints it was decided to use the AINA camp power supply. This essentially ruled out the chance of operating the equipment on the Col, because of the weight of the 5 kw generator involved and the prevailing soft snow conditions at that time. The transmitter and receiver were kept inside the hospital building at room temperature, while the antenna (minus the reflector screens) was supported horizontally so that the two antennae pods were about 0.5 m above the snow surface. The equipment was operated at different combinations of bandwith (10,30 mHz) and pulse-width (100, 250, and 500 ns). The echo-grams were not of the same type as those obtained from pure (cold) ice resting on bedrock, but a broad perturbation seems to occur where the bed position might be expected. This "perturbation" is characterized by a steep front, but has a diffuse decay profile; the position varied slightly with different (pulse/band) width settings. Figure 6 shows a sketch of one of the echograms.

The average return time of six values gave 1.378 μs which, when using a conversion value of 200 m/μs (Jones, personal communication), yields

Fig. 6. Echogram for AINA camp site.

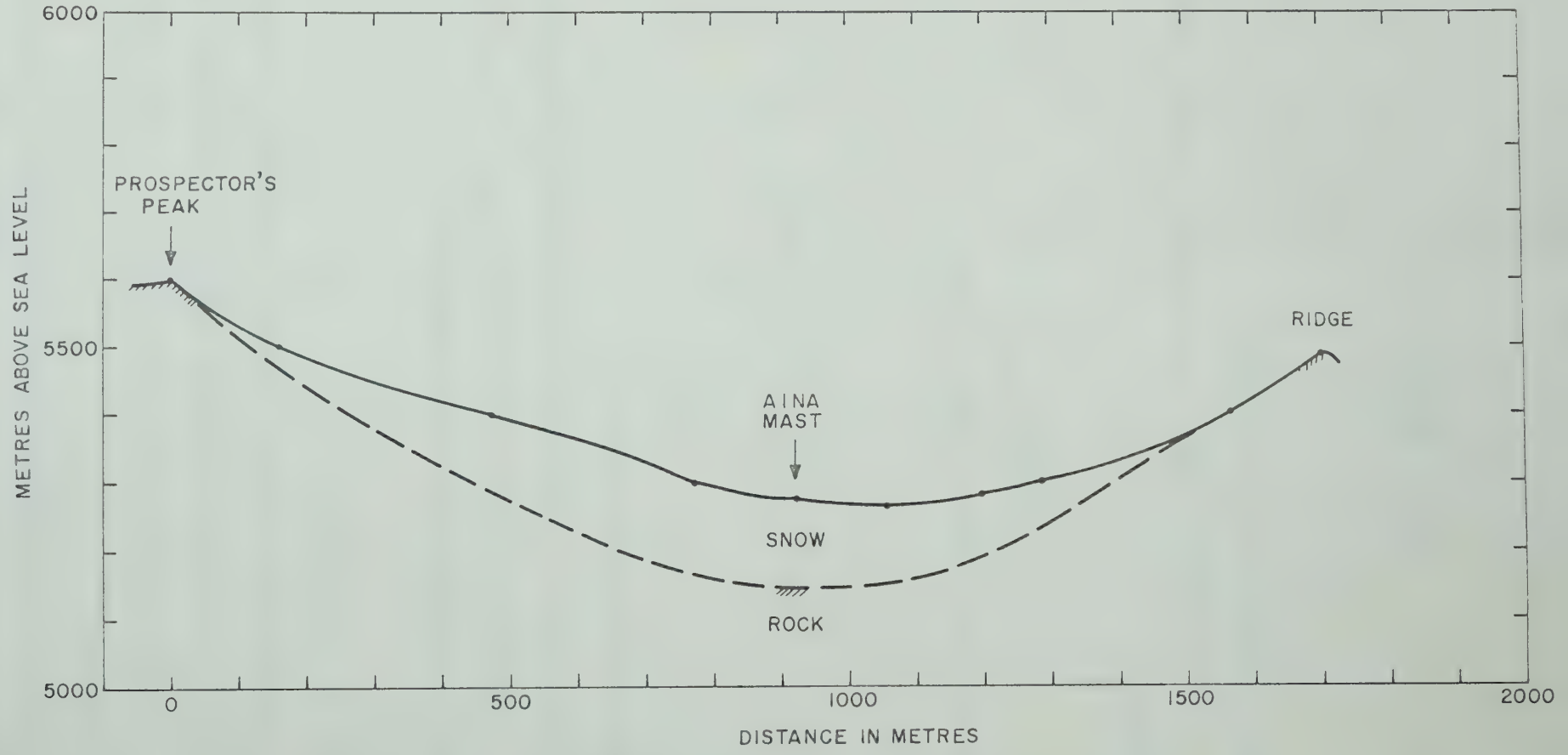


Fig. 7. Cross-section of plateau through Arctic Institute of North America mast and camp site.

a depth of firn-ice of 137 m ± 11 m. This depth value is within about 30 m from the AINA mast, at which location the ice velocity measurement applies, (Fig. 7 and Fig. 8).

In order to determine the reliability of the radio-echo value, we have done some computations using the surface velocity value, surface slope, and flow law constants available from the literature, taking into account the correction for temperature.

Computation of firn-ice depth at AINA mast site:

We make the simplifying assumption of laminar flow and use the classical Nye solution (Nye, 1952) for the velocity component parallel to the surface of a parallel sided slab:

$$u = \frac{1}{n+1} \left(\frac{\rho_i \, g \sin \alpha}{B} \right)^n . H^{n+1} \qquad (6)$$

where the flow law is of the form $\dot{\gamma} = (\frac{\tau}{B})^n$

and $B \propto \exp(-Q/RT)$.

Solution No. 1

If we assume a linear viscous law, B becomes simply the viscosity (in shear), η, and (6) can be rewritten

$$H = \sqrt{\frac{2 u \eta}{\rho_i \, g \sin \alpha}} \qquad (7)$$

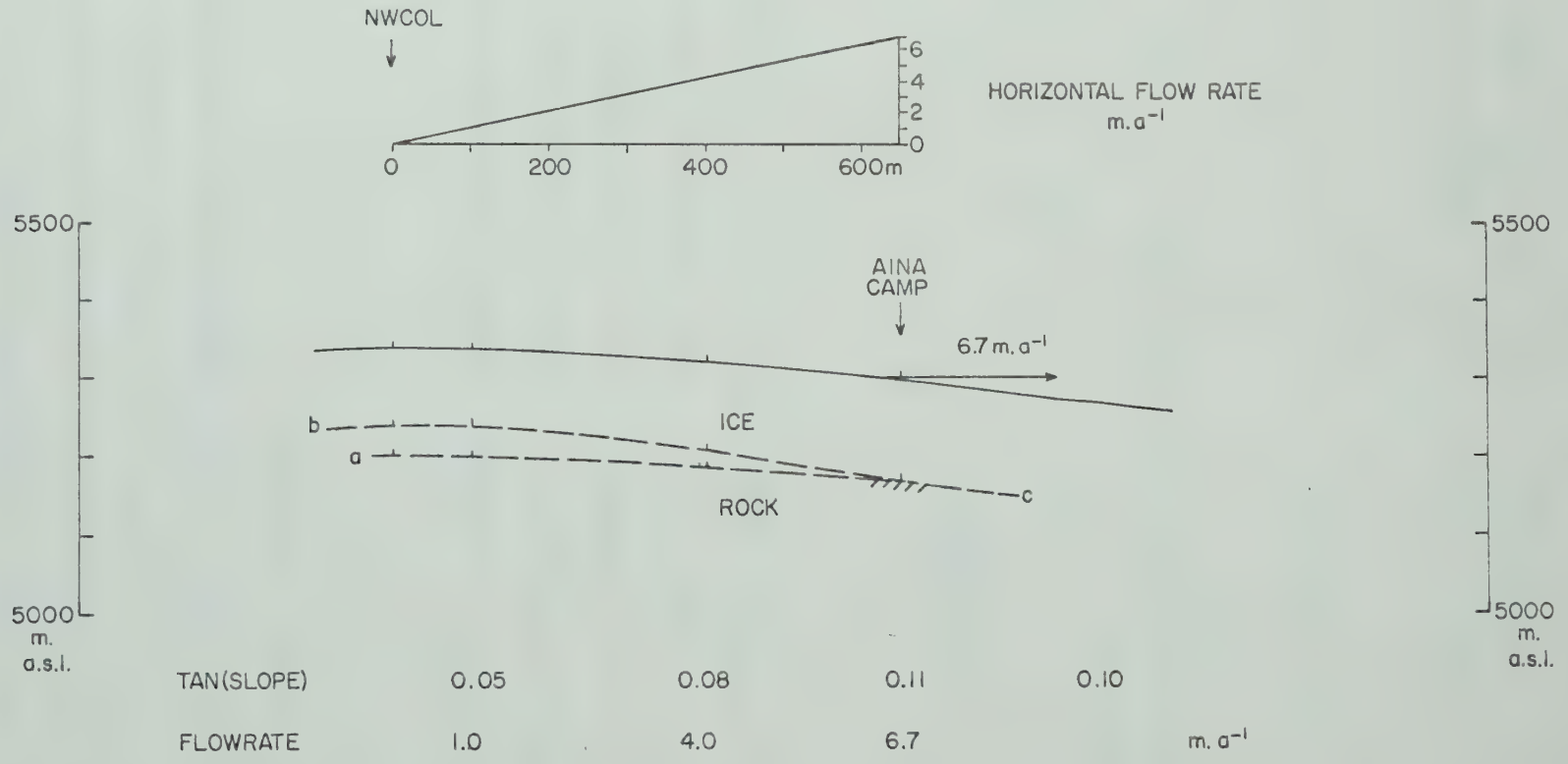


Fig. 8. Longitudinal snow/firn thickness profile from the NW Col to AINA mast.

Since the depth is to apply at the AINA camp, we take Keeler's temperature value and assume the average ice temperature is about - 24.5°C, although over the full column it will likely be warmer than this, Mellor and Smith, (1967) give values of viscosity of snow/firn for different temperatures and densities and a value of $\eta = 1.6 \times 10^{11}$ g. cm^{-2}s has been taken from their data. Using (7) this yields a value of H = 122 m.

Solution No. 2

Haefeli (1967) has retained a power flow law to characterize firn deformation and has provided values of the flow law constants with temperature and density. In this case, however, a standard temperature of -10°C is used and it is necessary to convert to the colder temperature. This can be easily done using the Boltzmann equation (see Mellor, 1963) with the result that

$$\frac{\dot{\gamma}\ (-24.5^{\circ}C)}{\dot{\gamma}\ (-10^{\circ}C)} \approx 0.2$$

where $\dot{\gamma}$ is the strain rate.

Haefeli (1967) expresses the flow law as

$$\dot{\gamma} = k_1 \left(\frac{\tau}{\tau_1}\right)^n \qquad (8)$$

where τ is the shear stress and $\tau_1 \equiv 1$ kg cm^{-2}. Converting to the usual form we get $B = k_1^{-1/n} \cdot \tau_1$. Evaluating, $B = (0.2 \times 10^{-7})^{-1/3} = 3.684 \times 10^5$ g. cm^{-2} $sec^{1/3}$; (n=3).

Hence H = 144. m

It is seen that both these calculated values are of the same order as the measured value, and are within 10% of it.

In order to compute firn thicknesses toward the Col, we have resorted to the use of equations (6) and (8), using an assumed linear increase in velocity with distance from the divide and the surface slope as determined from the map. Thicknesses are shown in Figure 6. At the crest (6) becomes indeterminate, so the computations have been stopped 100 m either side of the crest. A possible firn thickness of at least 100 m on the NW Col is thus indicated (Fig. 8, ac). However, a cross profile drawn through the NW Col indicates the depth might be less than 100 m (Fig. 8, bc) and could be as thin as 60 m.

Depth-Time relation for the NW Col:

A successful model for determining the depth-time relationship is due to Dansgaard and Johnsen (1969). However, their model does not formally deal with the compaction thinning of the annual layers, since in their case they are dealing with total ice thicknesses nearly 2 orders of magnitude greater than our case, and consider annual layers only in terms of the equivalent ice thickness. Bader's theory (e.g. Bader, 1960) is capable of handling compaction thinning of layers, but is valid only down to about 20 m below the surface. Clearly, we have to deal with the case where plastic layer thinning (covered by the Dansgaard-Johnsen theory) is combined with compaction thinning of layers (covered by a Bader-type approach) in order to accurately derive a depth-time relationship. In the absence of suitable theory, we will use the Dansgaard-Johnsen model with several approximations. Firstly the annual accumulation at the surface λ_H, will be expressed in terms of the equivalent thickness of material of density 0.66 Mg m^{-3}, which is the average

density of the total column - by prior estimate 100 m long. Thus we consider a ficticious material of uniform density 0.66 Mg m^{-3} and thickness 100 m to be deforming by plastic thinning only. Let h be the height above the bottom where the horizontal flow rate changes from a linear function to a constant value up to the surface. We take h/H = 0.3, as Dansgaard and Johnsen did. The ordinate y is measured upward from the bottom, and t is time in years. The Dansgaard-Johnsen solution is:

$$t = \begin{cases} \dfrac{(2H-h)\tau}{2\,\lambda_H} \ln \dfrac{(2H-h)}{(2y-h)} & h \leq y \leq H \\ t_h + \dfrac{(2H-H)\tau}{\lambda_H}\left(\dfrac{h}{y} - 1\right) & 0 \leq y \leq h \end{cases}$$

$(\tau \equiv 1 \text{ year})$

Using a $\lambda_H \simeq 1.4 \times \dfrac{0.349}{0.66} \sim 0.7$ m firn

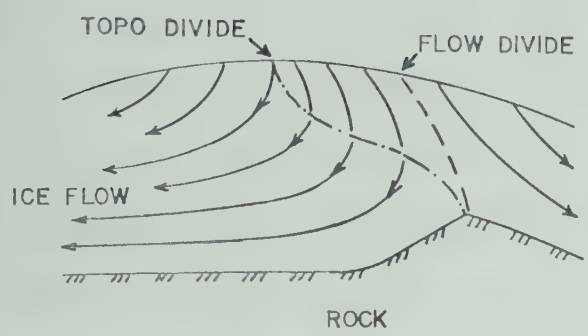
$t_h = 211$ years, corresponding to a depth of 70 m below the surface.

(For y = 1 m off the bottom, t = 7253 years).

However, long before this time, thinning of layers will be such that sampling will not be practical. The determination of layer thickness by applying the Dansgaard-Johnsen method will be quite rough but an estimate is, $\lambda_h = 0.12$ m at depth 70 m below the surface, and at t = 1000 years ago (about 7.2 m above the bed) the layer thickness is about 1 mm. If the total ice thickness is only 60 m, the corresponding values are $t_h = 126$ years (42 m depth); t = 2603 years at 59 m depth; $\lambda_h = 0.12$ m at 42 m depth; at t = 1000 years, $\lambda \simeq 1$ mm.

Conclusions

1. A more refined age-depth relationship should be derived.
2. A tritium analysis should be performed from the surface down to about 20 m in order to identify other peaks and pick up the 1954 bomb layer.
3. The oxygen isotope data indicate that seasonal fluctuations of $\delta^{18}O$ exist and hence annual layers can be identified. However, there appears to be a reversal in the peaks, with less negative values occurring in winter. This effect was also observed by West (1972). Temperature trends may also be determined from the data. A considerable amount of interpretation remains to be done.
4. The strain network on the NW Col when remeasured, together with the sinking rate should provide a check on our value of λ_H and the steady state assumption. The same holds for the AINA mast site.
5. It appears that the NW Col site might yield at least several hundred years of climatic information.
6. Provided a situation as shown in Figure 9 is not revealed the age-depth relationship should be straight forward. More ice bottom data is needed. In 1976, further echo-sounding with the 440 mHz instrument will be done.



g. 9. Hypothetical divide (After Haefeli, 1963) where topographic divide does not coincide with the flow divide. Analysis of a core retrieved from the topo divide will be complicated by significant horizontal flow at lower depths.

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FIGURE CAPTIONS

Fig. 1. Map of NW Col area.

Fig. 2. Tritium variation with depth at NW Col site.

Fig. 3. $\delta^{18}O$ variation with depth at NW Col site.

Fig. 4. Depth-density curve for the NW Col site.

Fig. 5. Vertical temperature profile at the NW Col site.

Fig. 6. Echogram for AINA camp site.

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Fig. 9. Hypothetical divide (After Haefeli, 1963) where topographic divide does not coincide with the flow divide. Analysis of a core retrieved from the topo divide will be complicated by significant horizontal flow at lower depths.

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Drafting of figures was done by the drafting section, Inland Waters Directorate. Acknowledgements for work resulting in the map (Fig. 1) are shown on that sheet.

Finally, I am indebted to Dr. Olav Løken for overall encouragement on this project.

PROVISIONAL MAP OF THE N.W. COL AREA OF MOUNT LOGAN YUKON TERRITORY - CANADA -

SCALE 1:10,000

METRES 200 0 200 400 600 800 1000 METRES

GRID INTERVAL 100 METRES CONTOUR INTERVAL 20 METRES.

DATUM 2000

LEGEND
- Occuppied station (rock).
- Occupied station (snow).
- Intersected point.
- Rock areas.

AERIAL PHOTOGRAPHY: ROLL No A-22 998 11 August 1972.
Altitude 12 200 metres, (40,000 feet), A.S.L.
Exposures 39 - 41.

Ground control Dr. G. HOLDSWORTH (Glaciology Division, D.O.E.) 1975
Plotting P. CRABTREE (Surveys & Mapping Branch, E.M.R.) 1976
Cartography J.L. CROIZET (Inland Waters Directorate, D.O.E.) 1976

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